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Chapter 13

FUNDAMENTALS OF MICROELECTROMECHANICAL SYSTEMS (MEMS) TECHNOLOGY AND PACKAGING

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WHAT ARE MEMS?

In the United States, the technology is known as microelectromecahnical systems (MEMS), in Europe as microsystems technology (MST), and in Japan as Micromachines. MEMS device microstructures differ from the integrated circuit (IC) elements, which sense or control processes that are mechanical, physical, chemical, optical, and biological. MEMS in its broader definition is a set of miniature technologies that make it possible to mass produce large numbers of integrated sensors, actuators, and communication systems that can be embedded within products or spread throughout the environment. Examples are shown in Figure 1 that includes: Vibratory Microgyro, Mars Seismometer, Microhygrometer, Miniature Mass Spectrometer, and electronic nose.

WHAT ARE MEMS APPLICATIONS TODAY AND TOMORROW?

The majority of today's MEMS products are components or subsystems and their main emphases are on the system levels. Current applications include accelerometers, pressure, chemical, and flow sensors, micromirrors, gyroscopes, fluid pumps, and inkjet print heads. For example, accelerometers are widely used for airbag deployment safety systems in automobiles. The current generation of accelerometer devices integrates electronic circuitry with a micromechanical sensor to provide self-diagnostics and digital output. It is anticipated that the next generation of devices will also incorporate the entire airbag deployment circuitry that decides whether to inflate the airbag. As the technology matures, the airbag crash sensor may be integrated one day with micromachined sensors to form a complete microsystems responsible for driver safety and vehicle stability.

Future and emerging applications include high-resolution displays, high-density data storage devices, valves, and fluid management, and processing devices for chemical microanalysis, medical diagnostics, and drug delivery. Current technology mainly addresses millimeter (mm) to micrometer (μm) level MEMS devices. Devices are being further developed in the range of submicron to nanometer scale (nano electromechanical systems, NEMS) for various applications.

A MEMS solution with lighter weight becomes attractive if it enables a new function, provides significant cost reduction, or both. For instance, medical applications generally seem to focus on added or enabled functionality and improved performance, whereas automotive applications often seek cost reduction.

MEMS DEVICES

Sensors and actuators are the two main categories of MEMS. Examples of commercially available sensors and actuators are:

- Pressure sensor which are used for a wide variety of differential, gauge, and absolute pressure base on different transduction principles and are fabricated by a microfabrication technique called bulk micromachining, i.e. by etching large amount of material
- Accelerometers depending on design are fabricated by bulk or surface micromachining. If a large mass suspended with spring, then the bulky mass is fabricated by bulk micromachining. If on the other hand, interdigitated beams are used, then surface micromachining enable formation beams, i.e., by addition of thin film layers, patterning, and then etching.

The following sections will review materials requirements, microfabrication techniques, and current packaging practices for MEMS followed with an example for pressure sensor using bulk micromachining technique and an accelerometer using surface micromachining. Finally, reliability and common failure mechanisms are discussed in comparison to ICs.

MATERIALS PROPERTY REQUIREMENTS FOR MEMS

Silicon for MEMS

MEMS is the next advanced technology step in the silicon revolution which began near four decades ago, with the introduction of the first integrated circuit (IC). Silicon is the primary substrate material for microelectronic IC and is also the most suitable candidate for MEMS due to its unique microfabrication characteristics. Silicon as an element exists in crystalline, polycrystalline (polysilicon), and amorphous forms. Polysilicon and amorphous silicon are usually deposited as thin films with thicknesses below 5 μm.

Silicon can be economically manufactured in single crystal substrates. Silicon is a suitable material on which electronic, mechanical, thermal, optical, chemical, and even fluid flow functions can be integrated. The precise modulation of silicon's electrical conductivity using impurity doping lies at the very core of the operation of electronic semiconductor devices. Ultrapure electronic grade silicon wafers available for the IC industry are also common today in MEMS. Silicon has a diamond lattice crystal structure, simple cubic, that its crystal planes etch rates allowing to form cavities with specific crystal planes. Crystalline silicon is hard and brittle material deforming elastically until it reaches its yield strength, at which point it breaks. Its tensile yield strength and average Young's modulus are 7 Gpa ($7x10^7$ N/M^2) and 160 Gpa, respectively.

Thin Film Materials for MEMS

Silicon nitride, silicon dioxide, and polysilicon thin films are the most common in semiconductor IC and MEMS fabrications. Silicon dioxide is used as a sacrificial layers (a layer eventually etched away) to fabricate polysilicon MEMS microstructures in surface micromachining. Silicon nitride layer serves as a mask material during chemical etching process of silicon.

Materials with Special Characteristics

Materials with unique reaction to physical parameters such as electricity with mechanical stress and magnetic field which results in a multitude of phenomena also of great interest to MEMS. For example, piezoresistivity, a phenomenon by which an electrical resistance changes in response to mechanical stress, is widely used as physical effect in stress sensors.

MICROMACHINING FABRICATION

Micromachining is a set of design and fabrication tools that precisely micromachine and form microstructures for ICs and MEMS. Micromechanical parts such as diaphragm and cavity for pressure sensors and suspension mass and beam for accelerometers are fabricated by this technique. The technique was demonstrated in silicon, glass, ceramics, polymers, and III-V semiconductors, titanium and tungsten. However, silicon remains the primary material of choice for MEMS. The micromachining can be subtractive by removal of significant region of substrate (bulk micromachine) and additive by build up and patterning thin-film layers to fabricate the desired microstructures on substrate (surface micromachine).

General Micromachining Processes

Several basic techniques are associated with silicon micromachining, i.e., deposition of thin films and removal of materials by wet/dry etching techniques using photolitography.

Thin films

Various techniques are used to deposit or form thin films in micrometers on a wafer substrate, e.g., silicon. The films can then be patterned, i.e. define the shape of micromachined structure, using photolithography and an etching technique. Common thin film materials include: silicon dioxide (oxide), silicon nitride (nitride), polycrystalline silicon (polysilicon or poly), and aluminum.

Photolithography is used to generate required patterns. A photomask, a nearly optically flat glass (transparent to near ultraviolet) or quartz plate (transparent to deep ultraviolet) with a chromium metal absorber layer pattern, is placed into direct contact with the photoresist coated surface, and the wafer is exposed to the ultraviolet radiation using mask aligner as shown in Figure 2. The chromium pattern on the photomask is opaque to ultraviolet light, where as glass or quartz is transparent. This procedure results in 1:1 image of the entire mask onto to the silicon wafer. Depending on photoresist process, the final microstructure may have a cavity (positive photoresist) or an excess layer (negative photoresist) as shown in Figure 2a and 2b, respectively.

Wet etching

Wet etching defines the removal of material by immersing the wafer in a liquid bath of the chemical etchant. Wet etchants fall into two broad categories; isotropic and anisotropic etchants.

Isotropic etching- Isotropic etchants attack the material at the same rate in all directions. Isotropic etchants are available for oxide, nitride, aluminum, polysilicon, gold, and silicon. Etchants remove material horizontally under the etch mask, i.e. undercutting, at the same rate as they etch through the material as shown in Figure 3.

Anisotropic etching- Anisotropic etchants etch different crystal planes in silicon at different rates, so there is more control of the shapes produced. The most popular anisotropic etchant is potassium hydroxide (KOH), e.g. selectively etch the {100} planes of silicon but not the {111} planes. The etch results in cavities that are bounded by {111} planes as shown in Figure 4. Both oxide and nitride etch slowly in KOH. Oxide, which can be used as an etch mask for short periods in the KOH etch bath, i.e., for shallow grooves and pits. For long periods, nitride is a better etch mask as it etches more slowly in the KOH.

Rate-Modified Etching

Silicon etching rate in KOH will be reduced by several order of magnitude when enriched by boron, effectively stopping its etching. The boron impurities are usually introduced into the silicon by diffusion. A thick oxide mask is formed over the silicon wafer and patterned to expose the surface of the silicon wafer where the boron is to be introduced. The wafer is then placed in a furnace in contact with a boron diffusion source. Over a period of time, boron atoms migrate into the silicon wafer. Once the boron diffusion is completed, the oxide mask is stripped off. A second mask may then be deposited and patterned before the wafer is immersed in the KOH etch bath. The KOH etches the silicon that is not protected by the mask, and etches around the boron-doped silicon. Figure 5 shows an unetched boron rich silicon beam over a cavity formed by using anisotropic characteristics of silicon.

Boron can be driven into the silicon as far as 20μm over periods of 15 to 20 hours, however it is desirable to keep the time in the furnace as short as possible. With complex designs, etching the wafer from the front in KOH may cause problems where slow etching crystal planes prevent it from etching beneath the boron-doped silicon. In such cases the wafer can be etched from the back, however this is not without disadvantages (longer etching times, more expensive wafers, etc). The high concentration of boron required means that microelectronic circuitry cannot be fabricated directly on the boron doped structure.

Surface Micromachining

Surface micromachining is a process that employs two thin film materials, a structural material (polysilicon) and a sacrificial material (silicon dioxide). These films are deposited and plasma/dry etched. The sacrificial material is finally chemically etched to release polysilicon microstructures. Detail process flow is shown below and schematically are drawn in Figure 6, steps a through g.

a Grow silicon dioxide: Silicon dioxide is first grown thermally on a silicon substrate, e.g., in a water vapor at 1000°C for 1 hr. The result is change of silicon surface to silicon dioxide which is controlled by diffusion of water vapor through oxide. This process is slow and the nonstoichiometeric silicon oxide film is highly stressed. The oxide also can be deposited using CVD or PECVD (chemical vapor deposition or plasma enhanced CVD) without modifying the substrate surface.

b Apply photoresist: Photoresist is a photosensitive material suspended in a solvent that is next applied to the surface of the silicon dioxide/Si substrate. This is typically done by spin coating. The photoresist is then soft baked to drive the solvents off.

c Expose and Develop: The photoresist is then exposed to ultraviolet light (UV) through a photomask. The exposed area is then developed by selective etching in potassium hydroxide (KOH), a positive photoresist.

d Etch silicon dioxide: The silicon dioxide is then etched using either plasma or chemical etching. The photoresist act as a hard mask, which protects sections of the silicon dioxide. Etchants are classified as wet (i.e. HF, HF + NH_4F) or dry (i.e. plasma etch, NF_3). The photoresist is removed by a wet (i.e. piranha = sulfuric acid and hydrogen peroxide) or dry process (i.e. ash or oxygen plasma). The result is a silicon dioxide beam on the silicon substrate.

e Remove photoresist: The photoresist protecting the polysilicon beams is next removed using an acetone solvent.

f Deposit polysilicon: Polysilicon is next deposited over the silicon dioxide beams. Polysilicon is typically deposited in an LPCVD (Low Pressure CVD) at temperatures near 600°C in a silane (SiH_4). Deposition rates are slow, near 70 Å/min. The low deposition rates limits film thickness and induce a significant internal stress for long duration growth process. The polysilicon must be stress free or have a tensile internal stress to avoid film buckling due to compressive stress.

g Remove Silicon Dioxide: Finally, the silicon dioxide is removed to develop polysilicon microstructures. A wet etch is commonly used to remove silicon dioxide since plasma etchant cannot easily remove the oxide confined under the polysilicon beam. A common wet etch is hydrofluoric acid which does not attack pure silicon and polysilicon. Free polysilicon beam will be formed after complete removal of silicon dioxide.

Bulk Micromachining

Bulk micromachining is used to fabricate diverse microscale movable mechanical pin joints, springs, gears, sliders, sealed cavities, accelerometer, micrormirrors, and many other mechanical and optical components. In bulk micromachining, three-dimensional features are etched into the bulk of crystalline and non-crystalline materials. Dry etching defines the surface features in the x and y plane and wet etching releases them from the plane by undercutting.

In wet bulk micromachining only the wafer thickness limits the feature height whereas this is a few micron for the LPCVD polycrystalline silicon films in surface micromachining. Therefore, bulk micromachining is suitable technique for introduction of large cavity in silicon for pressure sensor or forming an inertial mass for accelerometer. Polysilicon lacks thickness for rigidity and needs subsequent high temperature annealing after deposition. Detailed process steps involved in a typical bulk micromachining are shown in Figure 7. Note, steps are the same as those in Figure 6 with an exception of the step which uses anisotropic etching to develop a cavity in silicon.

Dry etching

The most common form of dry etching for micromachining applications is reactive ion etching (RIE) or deep RIE (DRIE). Ions are accelerated towards the material to be etched, and the etching reaction is enhanced in the direction of travel of the ion. RIE is an anisotropic etching technique. Deep trenches and pits (up to ten or a few tens of microns) of arbitrary shape and with vertical walls can be etched in a variety of materials including silicon, oxide and nitride. Unlike anisotropic wet etching, RIE is not limited by the crystal planes in the silicon as shown in Figure 8.

Lift off

Lift off is a stenciling technique often used to pattern noble metal films since they cannot be processed by chemical etching. Process steps are shown in Figure 9, a to d. A thin film of material, e.g., oxide, is deposited over silicon substrate, then a layer of resist is spin coated and patterned to expose the oxide. This is followed by wet etching to undercut the photoresist. The metal is then deposited on silicon by thermal evaporation which is effectively stenciled through the resist opening. Finally, the metal deposited over resist is removed by lift off using acetone solvent. The metal over oxide remains intact for subsequent MEMS device interconnects.

Excimer Laser Technique

The excimer laser (ultraviolet laser) is used to micromachine a number of materials including polymers. Unlike many other micromachining techniques, laser remove material by burning or evaporation.

LIGA Technique

LIGA is a technique for micromachining components which require high aspect ratio (ratio of the depth to the width) microstructures. A wide variety of materials can be used. It is a German acronym for lithographie, galvanoformung, and abformong, which refers to lithography, plating, and molding. These processes are based on standard semiconductor IC fabrication techniques and most importantly on lithographic pattern transfer using x-rays instead of UV. Figure 10 shows a typical LIGA process steps and examples of SEM photographs. The penetrating power of x-rays allows the fabrication of high aspect ratio microstructures on the order of millimeters in vertical and microns in horizontal dimensions with a ratio to 100. These microstructures are 3-D which are defined by 2-D lithographic patterns. One of the biggest advantages of LIGA is its ability to fabricate microstructures from different materials including metal, plastics, and ceramic. However, LIGA suffers since it requires X-rays from a synchrotron source.

MEMS PACKAGING

In the IC industry, electronic packaging must provide reliable, dense interconnections to the multitude of high-frequency electrical signals. In contrast, MEMS packaging must account for a far more complex and diverse set of parameters as shown schematically in Figure 11. It must first protect the micromachined parts in broad ranging environments; it must also provide interconnects to electrical signals, and in some cases, access to and interaction with the external environment. Examples are as follows:

1. The packaging of a pressure sensor must ensure that the sensing device is in intimate contact with the pressurized medium, yet protected from exposure to any harmful substances in this medium.
2. Packaging of valves must provide electrical and fluid interconnects.

The evolution of MEMS packaging is slow and research centers largely on borrowing from the IC industry in an effort to benefit from the existing mature technology. Designing packages, e.g. micromachined sensor, involves taking into account a number of important factors. Some of these are shared with the packaging of electronic ICs, but many are specific to the MEMS applications. The following are critical factors and consideration frequently encountered in MEMS packaging.

Wafer Stack Thickness

Standards in the microelectronic IC industry demands specific thickness for silicon wafers, depending on their diameters. A stack of bonded silicon or glass wafers can have thicknesses exceeding the norm for ICs, posing significant challenges for packaging foundaries.

Wafer Dicing Concerns

MEMS can be batch fabricated, ability to fabricate hundreds of identical microstructures or microsystems simultaneously on the same wafer. Releasing the MEMS microstructures may be performed either before or after dicing.

Before dicing- Dicing separates these structures into individual components that can be packaged at a later stage. Dicing is a harsh process conducted in an unclean environment and subject the MEMS mechanical microstructures and suspended thin films to a strong random vibration. Retaining the integrity and cleanliness of the MEMS microstructures requires protecting the sensitive components from particulates and liquids as well as ensuring that they can survive vibration.

After dicing- It is possible to perform the final sacrificial etch after the dicing is complete. While this "postprocess" approach ensures that there are no free MEMS micromechanical structures during dicing, it implies that the MEMS microstructures must be released on each individual die after dicing, thus sacrificing batch fabrication for mechanical integrity. This naturally increases the final fabrication cost significantly.

Thermal Management

In MEMS, the cooling of heat-dissipating devices, especially thermal actuators, involves understanding and controlling the sources of temperatures fluctuations that may adversely affect the performance of a sensor or actuator.

Unique Considerations

Unique properties of MEMS materials may be affected during packaging processes. For example, piezoresistive or piezoelectric elements must not be subjected to mechanical stress of undesirable origin, and extrinsic to the parameter that needs to be sensed. If they are stressed then:

a. Piezoresistive pressure sensor gives an incorrect measurement if the package housing subjects the silicon die to stress since piezoresistive elements are extremely sensitive to stress.
b. Device response may drift in long-term exposure due to accumulation of slow creep deformation in adhesive bonding of the silicon die to the package housing.

Protective Coating

MEMS sensors and actuators that will be exposed to environment must be protected against their adverse effects on reliability, especially for long-term exposures. In mildly aggressive environments, a thin conformal coating layer, e.g. parylene, is a sufficient protection. Extended exposure to highly acidic or alkaline solutions ultimately results in the failure of the coating. Silicon carbide may be used as coating for protecting MEMS in very harsh environments.

Hermetic Packaging

A hermetic package is theoretically defined as one that prevents the diffusion of helium (leak rate: $10^{-8}/cm^3$-sec). Hermetic package prevents the diffusion of moisture and water vapor through its walls. A hermetic package must be made of metal, ceramic, or glass. Plastic and organic–compound packages may pass helium leak rate test, but over time they allow moisture into the package interior; hence they are not considered hermetic. A hermetic package significantly increases the long-term reliability of electronic components performance and MEMS with high frequency moving parts. Hermetic MEMS package require excellent hermeticity and may includes a getter to absorb any residual gases/moisture in order to minimize frequency changes.

Die attach Processes

Subsequent to dicing of the substrate, each individual die is mounted inside a package and attached (bonded) onto a platform made of metal or ceramic by bonding. Die attach processes significantly influence thermal management and stress isolation. The bond must not crack over time or suffer from creep and its reliability must be established over very long periods of time. The choice of affects the mismatch in the coefficients of thermal expansion (CTE) with silicon which may results in undesirable stresses that can cause cracks in the bond.

Wiring and Interconnects

For MEMS similar to IC, the electrical connectivity can be performed by wire bonding, preferably gold over aluminum. Bonidg of wires are performed by thermocopression and ultrasonic techniques:

Thermocompression Bonding- In this technique, the die and the wire are heated to a high temperature (~250°C). The tip of the wire is heated to form a ball; the tool holding it then forces it into contact with the bonding pad on the chip. The wire adheres to the pad due to the combination of heat and pressure.

Thermosonic Gold Bonding- Thermosonic gold bonding is well-established technique in the IC industry, simultaneously combining the application of heat, pressure, and ultrasonic energy to the bond area. Gold wire bonding is preferable to aluminum. The use of wire bonding occasionally runs into serious limitations in MEMS packaging. For instance, the applied ultrasonic energy, normally at a frequency between 50 and 100 kHz may stimulate the oscillation of suspended mechanical microstructures. Most micromachined structures coincidentally have resonant frequencies in the same range, increasing the risk of structural failure during wire bonding.

Flip-chip

Flip-chip bonding involves bonding the die top-face-down, on a package substrate. Electrical contacts are made by means of plated solder bumps between bond pads on the die and metal pads on the package substrate. The attachment is intimate with a relatively small spacing (50 – 100 μm) between the die and the package substrate. What makes flip-chip bonding attractive to the MEMS industry is its ability to closely package a number of distinct dice (accelerometer, ASIC, yaw rate, etc.,) on a single package substrate with multiple levels of embedded electrical traces.

Types of Packaging Solutions

A package is a protective housing with an enclosure to hold one or more devices which with additional IC circuitry forms a complete MEMS system. Due to the variety of MEMS devices, it is not possible to specify a generic package. It is possible to make some general comments, however. The package must be designed to reduce internal/external electrical (or electromagnetic) interference, dissipate device heat, withstand high operating temperature, and minimize CTE.

Package should also be designed to minimize stress on the device due to external loading, and be rugged enough to withstand the environment in which the device will be used. Connections to the package must also be capable of delivering the power required by the device, and connections out of the package must have minimal sources of signal disruption (e.g. stray capacitance). The package also has to have the appropriate fluid feed tubes /optical fibers, etc, attached to it, and aligned /attached to the device inside. Three categories of widely adopted packaging approaches in MEMS are: ceramic, plastic, and metal, each with its own merits and limitations are discussed below.

Ceramic Packaging

A ceramic, a hard and brittle materials, package often consists of a base or a header onto which one or many dice are attached by adhesives or solder. Wire bonding is suitable for electrical interconnects. Flip-chip bonding to a pattern of metal contacts on the ceramic package works equally well. The final step after mounting the die on the base and providing suitable electrical interconnects involves capping and sealing the assembly with a lid, whose shape and properties are determined by the final application.

Plastic Packaging:

Plastic packages, unlike their ceramic or metal counterparts, are not hermetic. Two approaches to plastic packaging are: postmolding and premolding. The plastic postmolding housing is molded after the die is attached to a lead frame. The process subjects the die and the wire bonds to the harsh molding environments. In premolding, the die is attached to a lead frame over which plastic was previously molded.

Metal Packaging:

Metal packages are attractive for MEMS because they are robust and easy to assemble, but they are being replaced by plastic or ceramic packages. Metal packages satisfy the low pin-count requirements of most MEMS applications; they can be prototyped in small volumes with rather short turnaround periods and they are hermetic when sealed. For example, metal packaging of fluidic isolated pressure sensors are used for operation in heavily industrial environments. The silicon sensor is immersed into an oil filled stainless-steel cavity that is sealed with a thin stainless diaphragm. The sensor measures pressure transmitted via the steel diaphragm and through the oil. The robust steel package offers hermetic protection of the sensing die and the wire bonds against adverse environmental conditions.

Examples of MEMs Process and Packaging

Pressure Sensor-Bulk Micromachine

Figure 12 shows schematic drawing of a Manifold Absolute Pressure (MAP) sensor for engine control which designed to sense absolute air pressure within the intake manifold. The measurement is used to compute the amount of fuel required for each cylinder in the engine. This sensor combines advanced micromachining techniques, thin film metallization, and bipolar semiconductor processing to provide an accurate, high level electrical analog output signal that is proportional to applied pressure.

The sensor die/chip consists of a thin film Si diaphragm fabricated by bulk micromachining. Prior to the micromachining, piezoresistors are patterned across the edges of the diaphragm region using standard IC processing techniques (see Figure 7). After etching of the substrate to create diaphragm, the sensor is bonded to a glass substrate to be able to make a sealed vacuum cavity underneath the die diaphragm. Finally, the die is mounted on a standard IC package, e.g. a small outline leaded (SO), such that the top side of the diaphragm is exposed to the environment through a port. A gel coat isolates the sensor die from the environment while allowing the pressure signal to be transmitted to the Si diaphragm. The ambient pressure forces diaphragm to deform downward, resulting in a change of resistance of the piezoresistors. This resistance change is measured using on-chip electronics; a corresponding voltage signal appears at the output pin of the sensor package.

Surface Micromachine- Accelerometer

Figure 13 shows a monolithic accelerometer fabricated by surface micromachining processes. It is a comb-drive capacitive actuator which make use of a number of interdigitated "fingers" in which the deflection of comb changes the capacitance between the finger beams and the adjacent cantilever beams. The sensor structure is surrounded by supporting electronics transduce the capacitance changes due to acceleration into a voltage which is proportional to acceleration. Generally, accelerometers are housed in conventional low pin count packages including transistor outline (TO), dual-in-line (DIP), leaded ceramic package (Cerpak), plastic leaded package (PLCC), etc.

KEY FAILURE MECHANISMS OF MEMS DEVICES

Discussion on MEMS reliability is difficult questions since they are not well established yet, developed for specific applications, and depend on the user requirements. In spite of differences, common methodologies could be developed for assessing qualification and reliability for those with similar failure mechanisms. For IC package assembly, failure mechanisms are generally related to solders whereas for MEMS are more complex. Several key failure mechanisms for MEMS that are compared to IC packages in the following.

Failure by Stiction and Wear- Contrary to solder joint failure mechanisms for IC system, thermal cycling fatigue failure for MEMS are of less critical. Stiction and wear cause most failures for MEMS. MEMS failures may occur due to microscopic adhesion when two surfaces are come into contact which is called stiction. Microscopic separations generally cause particulates which when are trapped between micro parts will slow part movement. Wear due to corrosive environment is another aspect of such failure.

Delamination- MEMS may fail more often due to delamination than IC systems since they utilize much wider bonding applications. For example, delaminations of bonded thin film materials, and bond failures of dissimilar and similar materials such as wafer-to-wafer bonding.

Environmentally induced failures- Failure due to thermal cycling, vibration, shock, humidity, radiation effect, etc., are commonly observed for MEMS and IC packaging systems. MEMS devices because of having mechanical moving parts, are more susceptible to environmental failure than their IC packaging systems.

Cyclic mechanical fatigue- This is critical for comb and membrane MEMS devices where materials are subjected to alternative loading. Even if the load is significantly below failure, the stress can cause degradation in materials properties. For example, changes in elastic properties affect resonant and damping characteristics of beam and therefore degrade MEMS sensor outputs performance.

Dampening Effect- Dampening is not critical for IC packaging, but it is critical for MEMS devices, which operate with moving parts at their resonant frequency. Dampening can cause by many variables including presence of gas in atmosphere. Therefore, good sealing is essential for prevention of such failure.

SUMMARY

Microelectromechanical structures and systems are miniature devices that enable the operation of complex systems. MEMS exist today in many environments, especially automotive, medical, consumer, industrial, and aerospace. Their current and future applications are real and supported by strong developmental activities around the world.

The technology discussed included materials selection, microfabrication processes, packaging, and reliability associated with MEMS in reference to IC industry.

Two methods of microfabrication of bulk and surface micromachinings which utilize unique silicon characteristics were discussed. MEMS packaging techniques were reviewed and specific examples on pressure and accelerometer sensors were provided. It was shown that packaging for pressure sensors had to have access to interact with environment that may also degrade device performance due to corrosion. In contrast, packaging for accelerometer had to be hermetically sealed to avoid exposure to environment. Finally, failure mechanisms for MEMS were compared to their IC counterparts. Thermal cycling degradation of solder joint is key for IC package assembly whereas mechanical fatigue, stiction, hermeticity and wear are key factors for failure of MEMS with moving parts.

HOMEWORK PROBLEMS

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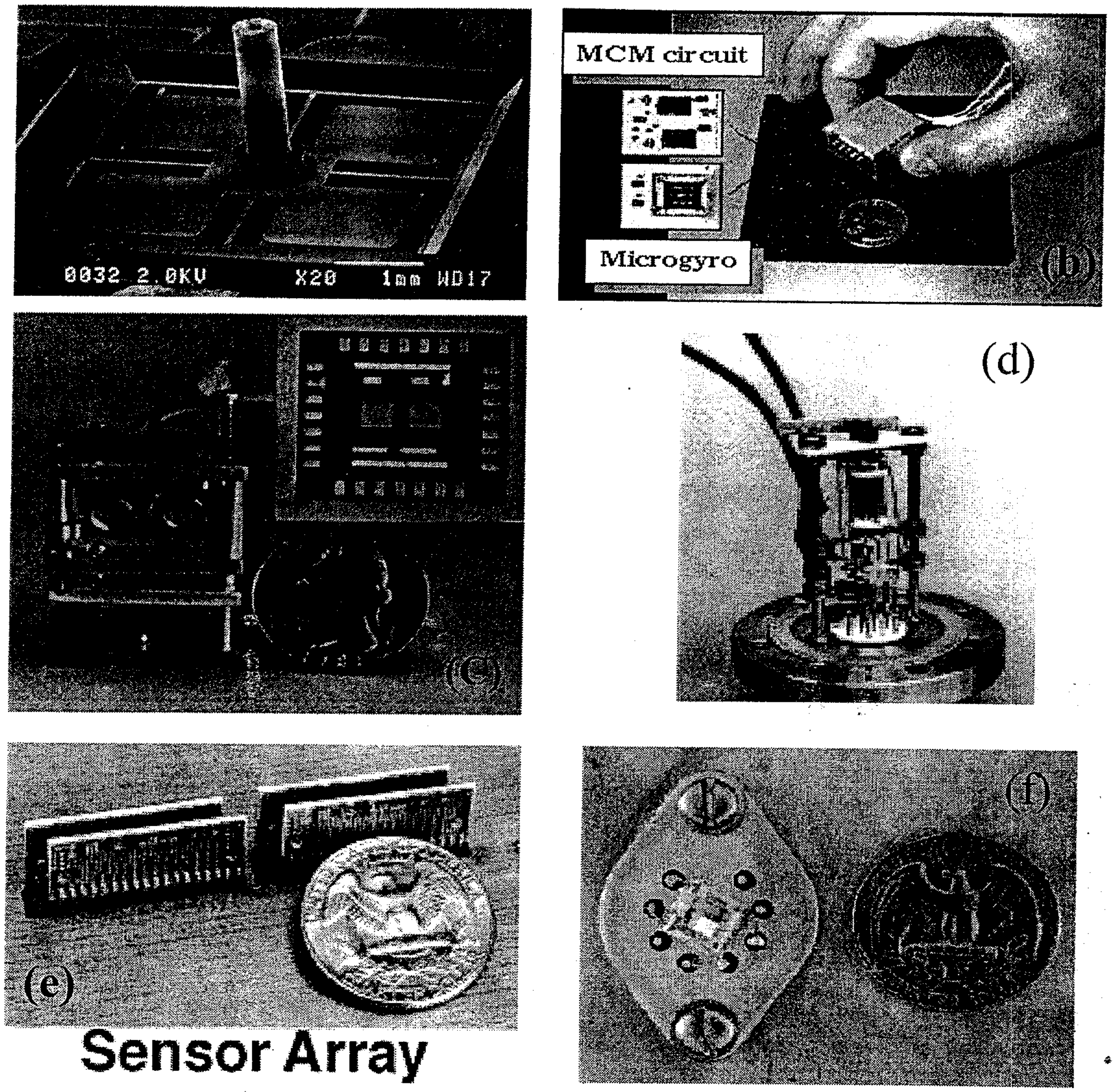
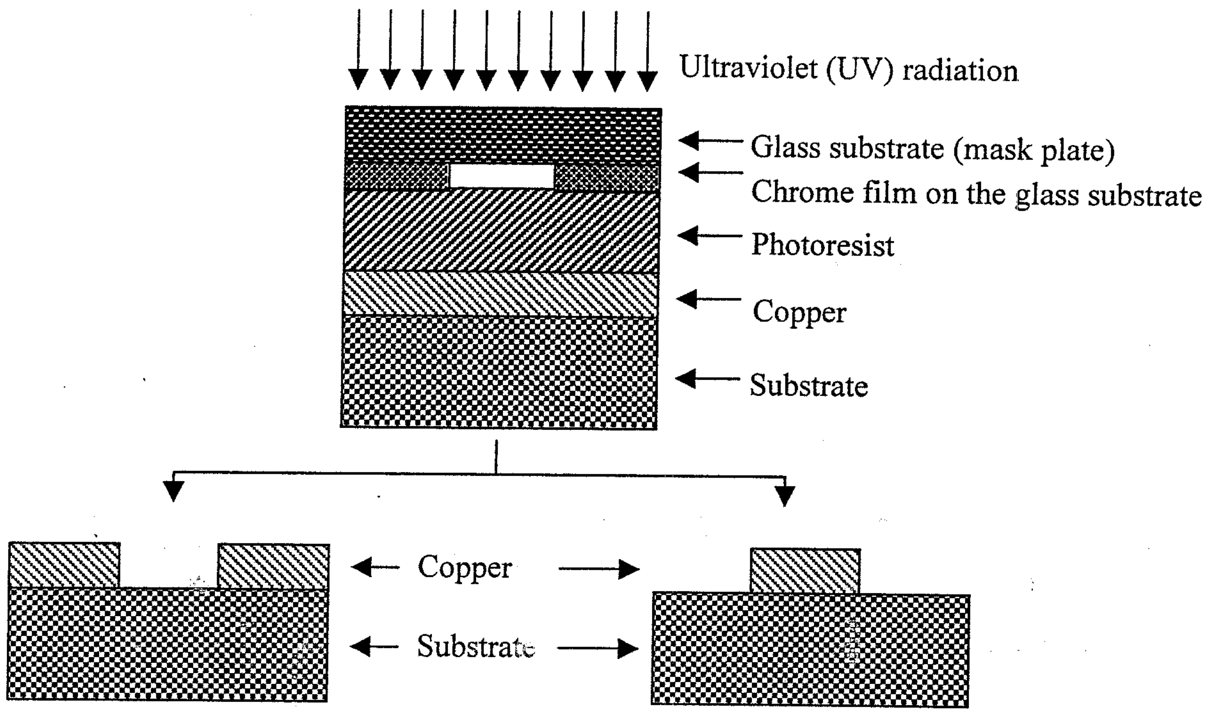


Figure 1: JPL/Caltech, NASA developed sensor devices: a. SEM of Vibratory Microgyro, (b) packaged microgyro, c. Mars Seismometer, d. Miniature Mass Spectrometer, e. E-Nose, and f. Microhygrometer (Courtesy of JPL/Caltech, NASA, Pasadena, CA)



(a) Positive photoresist process

(b) Negative photoresist process

Figure 2: Typical process steps involved in photolithography process when positive and negative photoresists used.

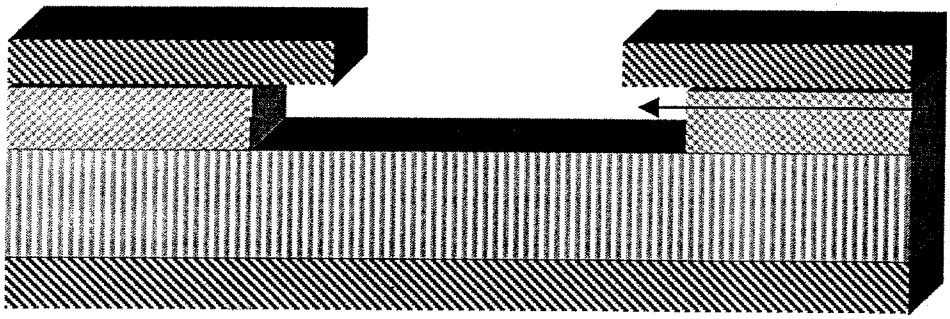


Figure 3: Isotropic etching of silicon and undercutting

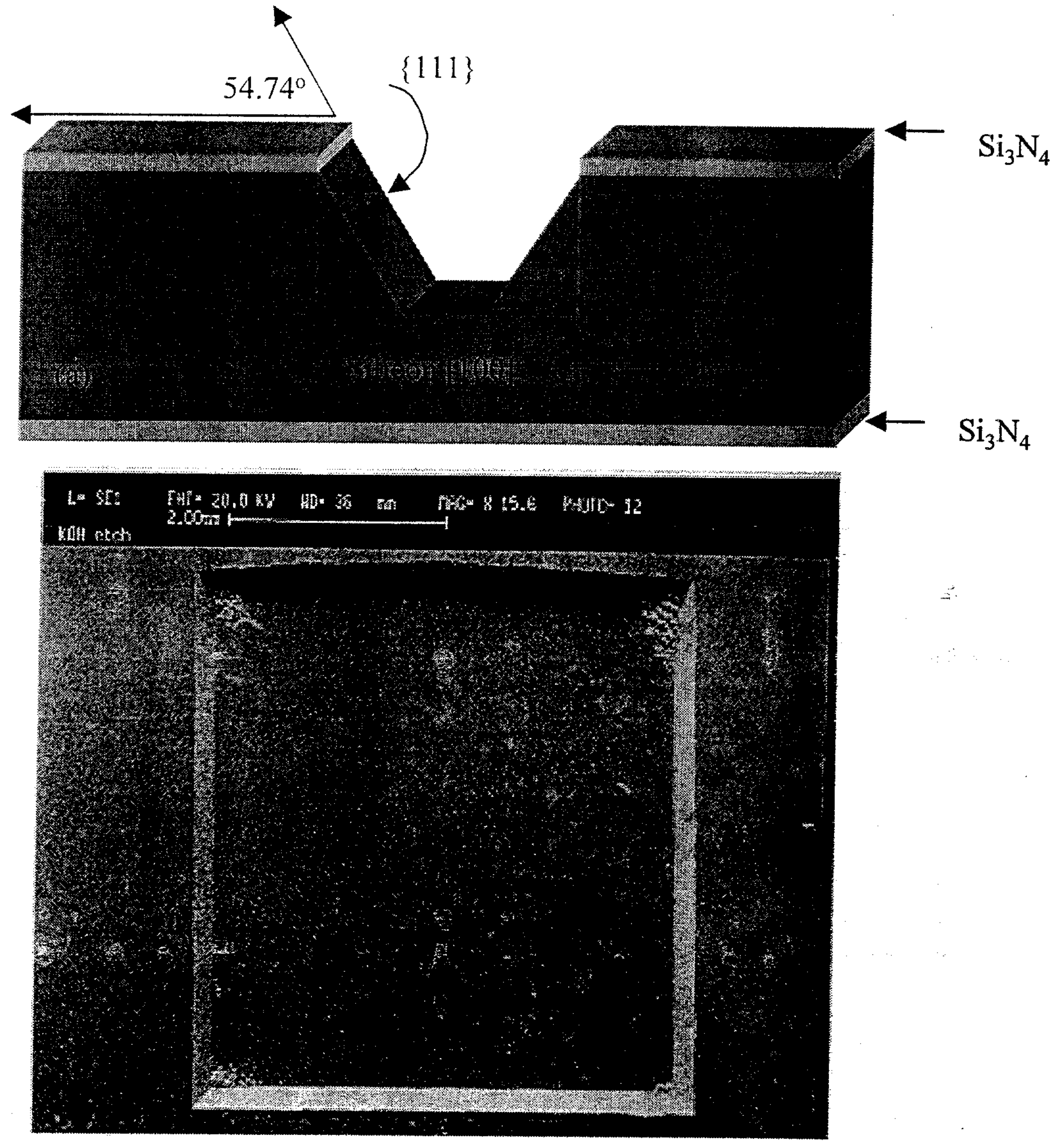


Figure 4: a. Schematic of anisotropic etching of silicon b. Anisotropic etching of silicon {100} substrate

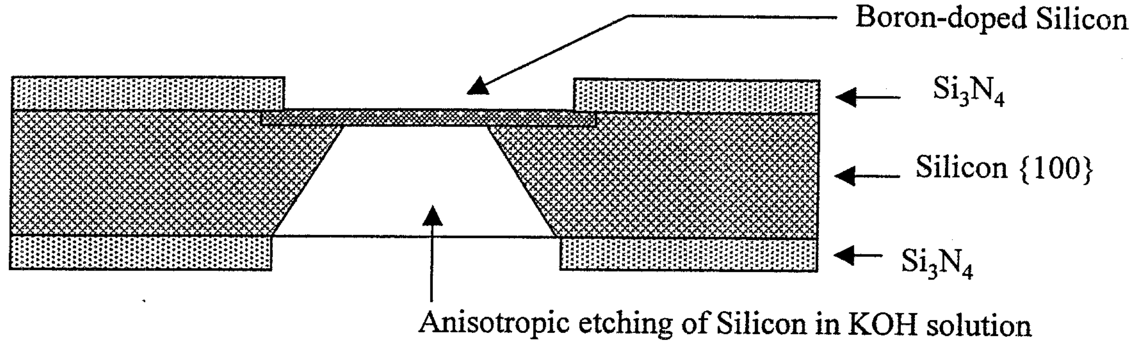


Figure 5: Boron-doped silicon as an etch-stop layer which aid in fabricating MEMS Microstructures

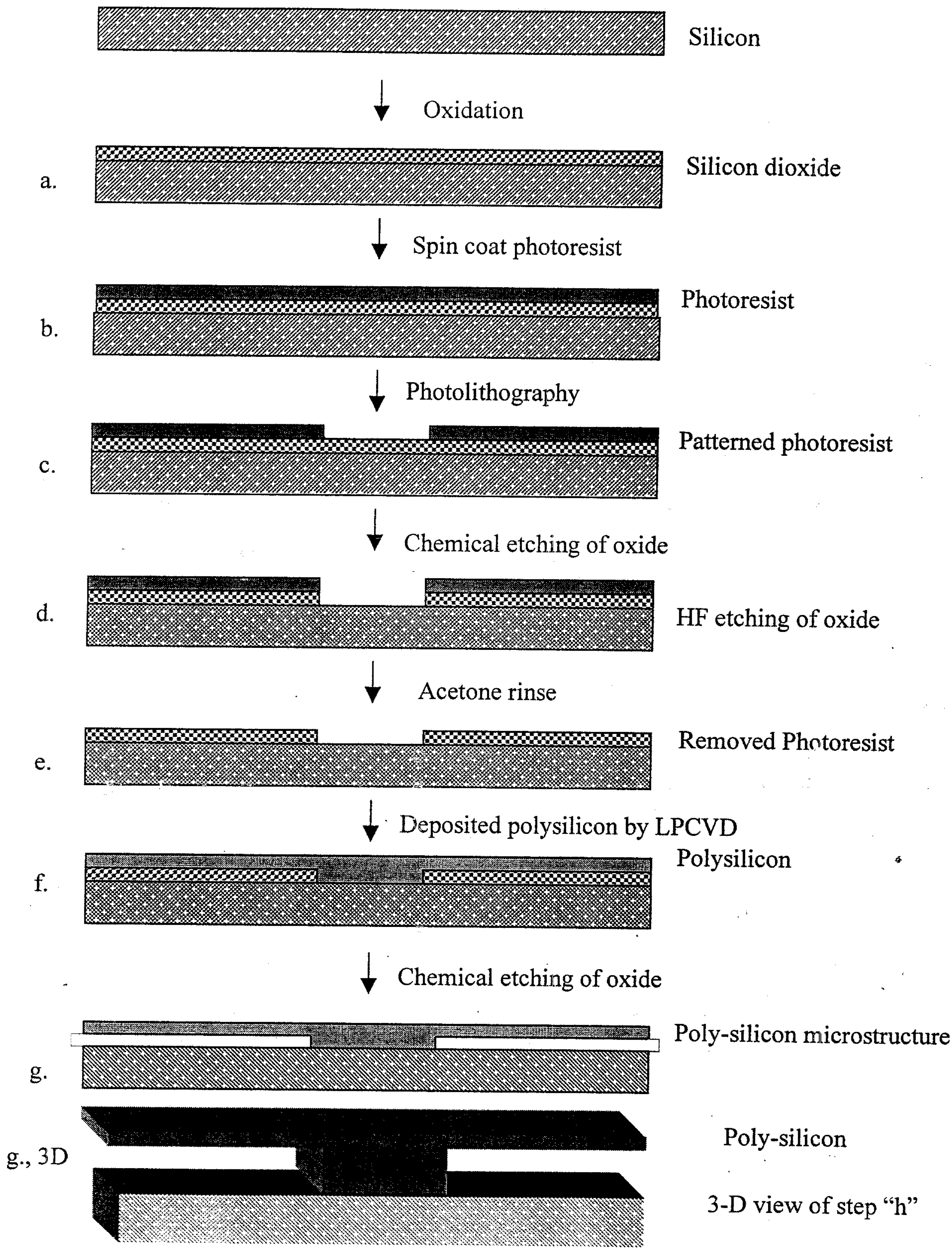


Figure 6: Schematic of Surface Micromachined Poly-silicon Beam

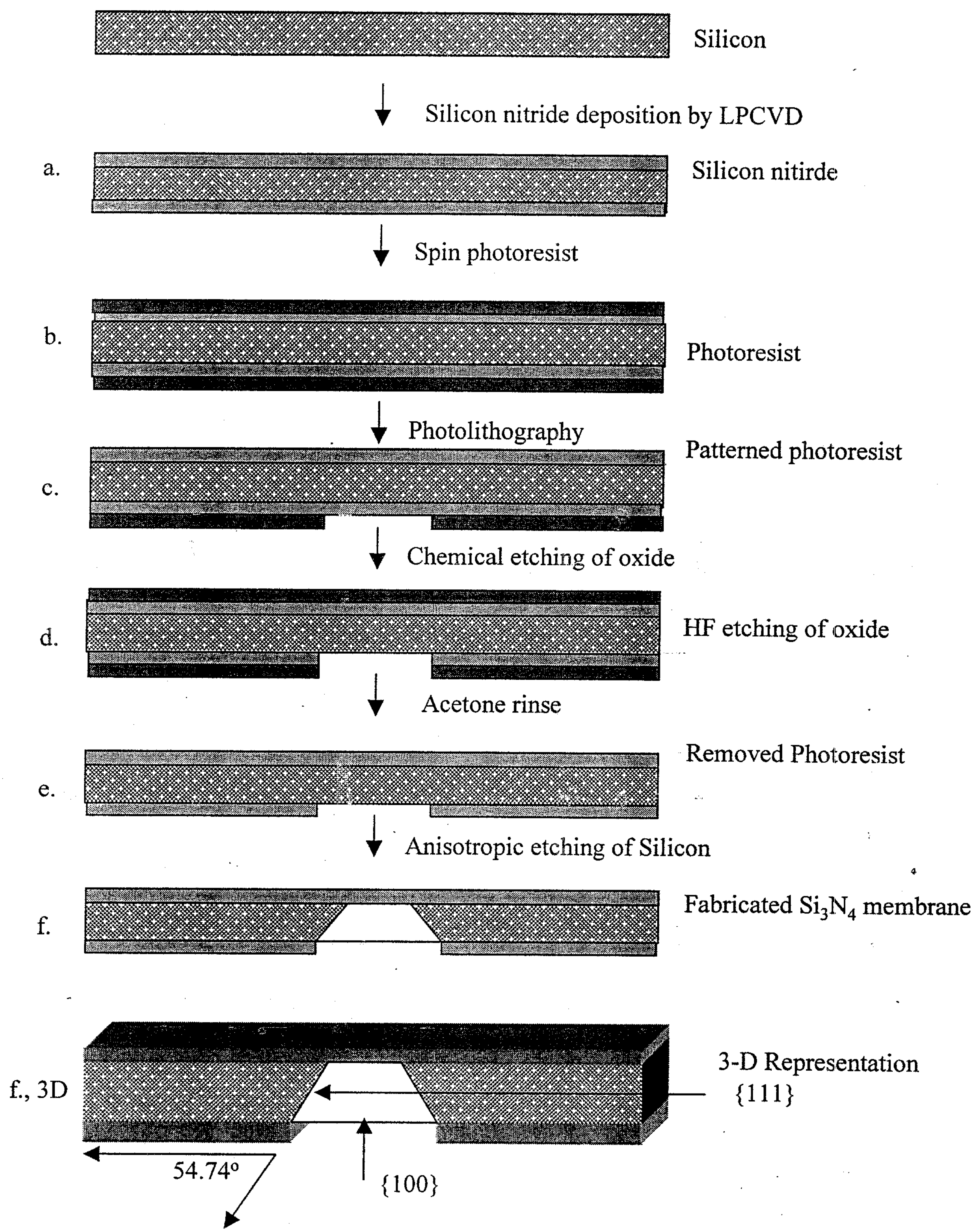


Figure 7: Bulk micromachined silicon {100} to fabricate silicon nitride membranes

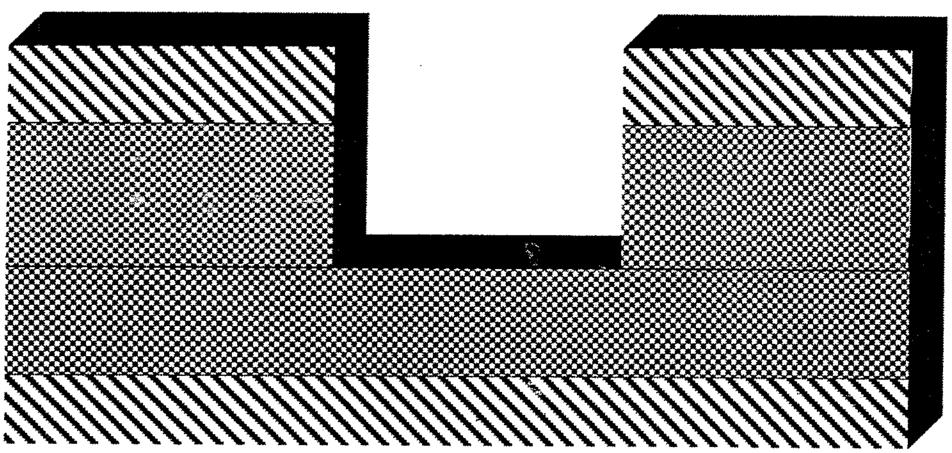


Figure 8: 3-D view of anisotropically etched silicon substrate using RIE or DRIE

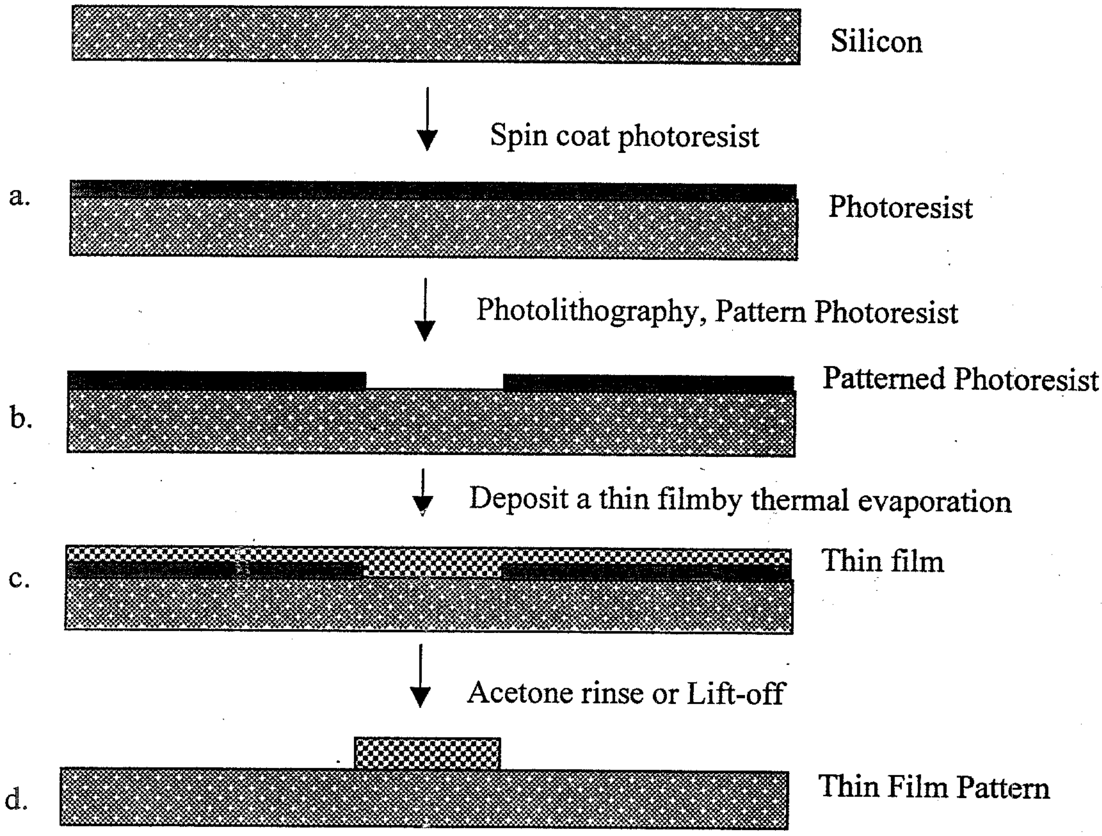


Figure 9: Typical steps involved in fabricating thin film patterns by lift-off

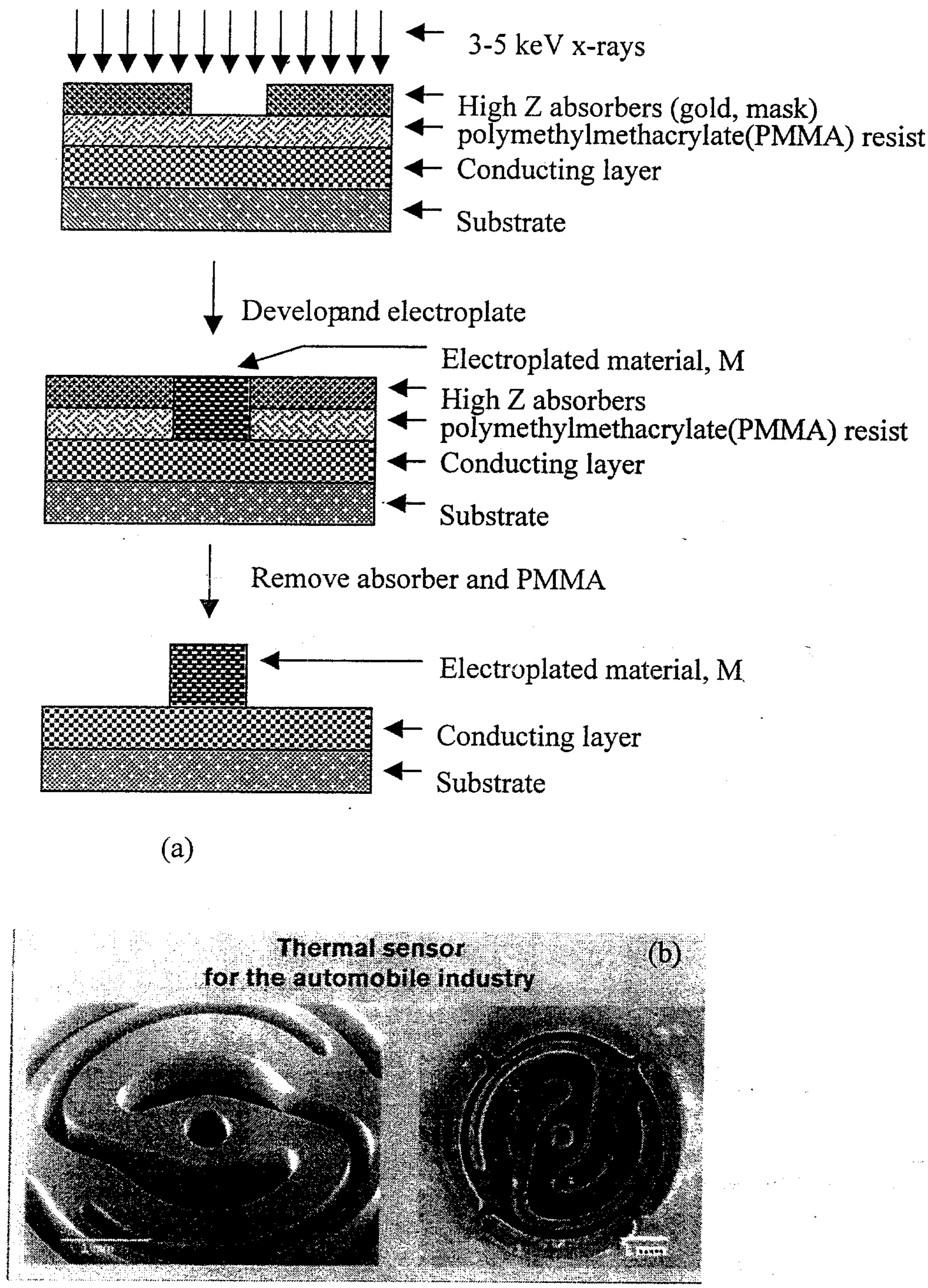


Figure 10. A. Schematic of typical LIGA process steps and b. SEM of LIGA microstructure

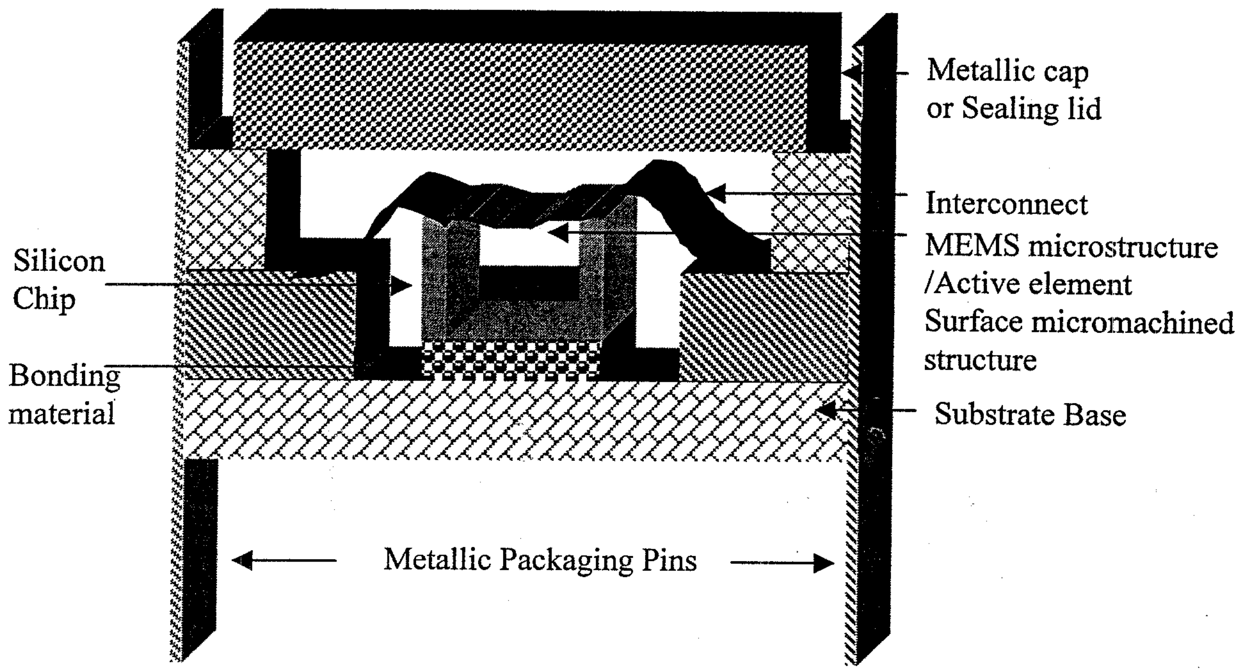


Figure 11. Schematic of MEMS packaging

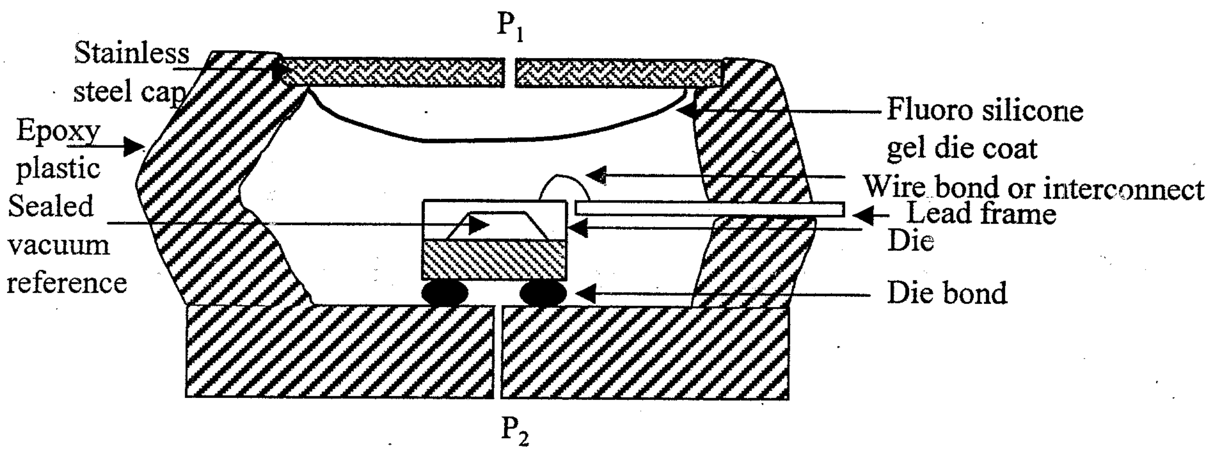


Figure 12. Cross-sectional diagram of an absolute pressure sensing die (Motorola)

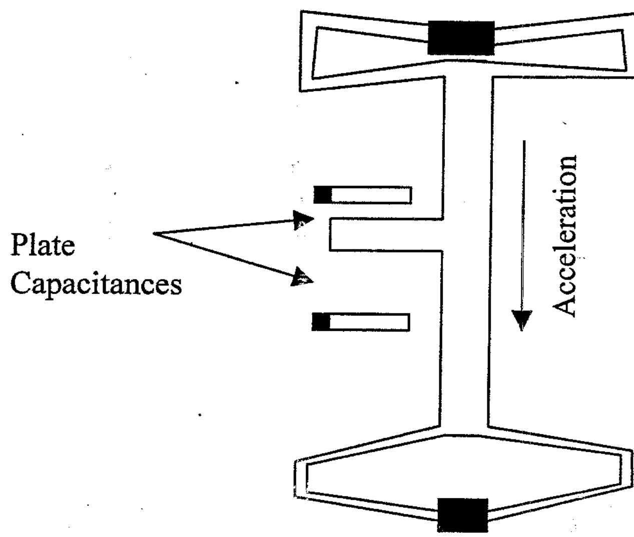


Figure 13: Schematic of accelerometer (Analog Devices)